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THE THERMAL CONDUCTIVITY AND DIFFUSIVITY OF CONCRETE

BY

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AND

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BULLETIN No. 122

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THERMAL CONDUCTIVITY AND DIFFUSIVITY OF CONCRETE

I. Introduction

1. *Object of the Investigation.*—The object of this investigation was to obtain the absolute thermal conductivity of a number of standard concrete mixtures. The diffusivity, or thermometric conductivity, has also been calculated from the specific heat, the density, and the thermal conductivity. The investigation was undertaken in response to inquiries for information as to such constants from engineers, received by the Engineering Experiment Station of the University of Illinois, but, apart from the need of such constants in present engineering problems, the increasingly numerous uses of concrete make determination of these physical constants for such a common material desirable.

In this investigation, it has been considered important to describe in detail the material for which the absolute thermal conductivity has been determined. During the last ten years the composition and methods of preparation of concrete mixtures have been studied and standardized, and the present investigators have had the advantage of dealing with concrete mixtures which can be described much more definitely than was possible a few years ago. The results of only a few determinations of the absolute thermal conductivity of concrete are recorded in the literature of the subject,* and to a large extent these lack definiteness in regard to the composition and method of preparation of the material, so that it is impossible to make more than a very general comparison of the results here recorded with those previously obtained.

* Proceedings of National Association of Concrete Users, Vol. VII, article by C. L. Norton. 1911.

"Thermo-conductivity of Heat Insulators," W. Nusselt. Engineering, Vol. 87, p. 1. Jan. 1909.

"A Study of the Heat Transmission of Building Materials" by A. C. Willard and L. C. Lichty. Univ. of Ill. Eng. Exp. Sta. Bul. No. 102, 1917.

Nusselt gives a single determination for "neat" cement, and he did not set a high value on this determination. The results of Norton and of Willard and Lichty will be noticed later in this bulletin.

In addition to determinations of the thermal conductivity of concrete, similar determinations for white marble were also made. The method used in the determinations for marble was the same as had been used for concrete. This not only gives an independently determined value of this constant for marble, but also links the determinations of thermal conductivity for concrete with those for a substance for which a number of values of the thermal conductivity are given in the literature on the subject.*

2. *Acknowledgments.*—In the preparation of the concrete specimens, we have received valuable help from the Department of Theoretical and Applied Mechanics of the University of Illinois. Professor A. N. Talbot, head of the department, has kindly advised with reference to descriptive terms for the material tested. To Mr. H. F. Gonnerman, formerly of the same department, thanks are due for advice and aid in the preparation of the large number of concrete cylinders. Mr. C. C. Schmidt, Assistant in Physics, aided Mr. Nelson, during the summer of 1920, in the preparation of the concrete cylinders and in the experimental work.

* The most extended series of determinations for marble are those of Professor B. O. Pierce and Mr. R. W. Wilson, published in the Proceedings of the American Academy of Arts and Sciences, Vol. 34, p. 3, 1898. They used a wall method, while the method used here was, as will be described, a cylinder method.

II. Principles and Methods of Measurement

3. *Definitions and Units.*—The fundamental fact of heat conductivity is that, for steady flow, the quantity of heat flowing in a unit of time through a plate varies directly as the difference of temperature between the faces of the plate, directly as the cross section of the plate, and inversely as the thickness of the plate. This law, which was first stated clearly by Joseph Fourier, the famous French military engineer and mathematician, is expressed by the formula

$$Q = k \frac{t_2 - t_1}{l} ST$$

In this equation, Q is the quantity of heat, $t_2 - t_1$ the difference of temperature at the two faces, S the area of the cross section, T the time of flow, and l the distance of flow, or the thickness. The quantity k is a constant, which is a property of the material of which the body is composed, and is called the *thermal conductivity* of the material. The fraction $\frac{t_2 - t_1}{l}$ is the fall of temperature per unit distance, and is called the *temperature gradient.*

The unit of thermal conductivity clearly depends upon the chosen units of length, area, time, and heat. In the following calculations a unit based on the centimeter, second, and gram-calorie, called here "the c.g.s. physical unit," has been used; but the results are stated also in a unit based on the foot, hour, and British thermal unit, called here "the British engineering unit." These units are defined as follows:

(a) *The C. G. S. Physical Unit* of thermal conductivity corresponds to the flow of one gram-calorie in one second, when the flow is steady, through a section of a plate of the substance in question one square centimeter in area, the thickness of the plate being one centimeter, and the difference between the temperatures of the faces of the plate one degree centigrade.

(b) *The British Engineering Unit* of thermal conductivity corresponds to the flow of one British thermal unit (B.t.u.) in one hour, when the flow is steady, through a section of a plate of the substance in question one square foot in area, the thickness of the plate being one foot, and the difference between the temperatures of the faces of the plate one degree Fahrenheit.

The conversion of results given in either of the above units into other units is a matter of simple calculation.

Upon this subject of units of thermal conductivity the following quotation is made from the excellent text-book of Ingersoll and Zoebel entitled "The Mathematical Theory of Heat Conduction": "There is probably no subject in which the confusion of units is greater than that of heat conduction. While the physicist uses the metric or c.g.s. unit—that is, the gram-calorie per second, per square centimeter of area, for a temperature gradient of a degree centigrade per centimeter —there is no such uniformity of practice among engineers. The steam engineer refers his observations to the B.t.u. per hour, per square foot, per degree Fahrenheit, per inch in thickness, while the refrigerating engineer prefers the day as the unit of time rather than the hour, and the electrical engineer uses various systems, based frequently on the kilowatt, as representing the rate of heat flow. There are also numbers of other units, some of them making use of the idea of thermal resistance, analogous to electrical resistance, and therefore being reciprocally related to conductivity. These various engineering units have been introduced to simplify the computation of heat losses in various types of problems, and on these grounds perhaps justify their existence; but from the standpoint of the present work they are, with one or two exceptions, not usable. This is because, in a large majority of the cases we shall have occasion to consider, it is not the conductivity but the *diffusivity,* or thermometric conductivity, which enters directly into the computations, and this latter is too complex a unit to use profitably with a mixture of English and metric systems, or an English system involving two different units of length—for example, feet and inches, as in common engineering practice. Only two, then, of the many heat-conduction units lend themselves readily to our purpose—the B.t.u. per hour, per square foot, for a temperature gradient of a degree Fahrenheit per foot, and the metric unit. But the former is practically never used (the gradient being expressed in degrees per *inch* in the common engineering unit), while the latter is becoming of more general use every day, so we shall confine our units and calculations to the metric system, giving in many cases, however, the English equivalents."

Thermal conductivity expressed in the units defined above, applies to the condition of steady flow, that is, the condition existing when the temperature at each point through the plate is not changing, and the

quantity of heat entering at one face is equal to the quantity emitted at the opposite face.

There is another constant, which is particularly important to the concrete engineer—namely, that which expresses the rate of flow of temperature for a material, or the *thermal diffusivity.* This evidently depends not only on the thermal conductivity, but also on the amount of heat required to raise the temperature of unit volume of the material one degree: that is, upon the density and the specific heat of the material. Thus, if D is the diffusivity, ρ the density, s the specific heat, and k the thermal conductivity of the material,

$$D = \frac{k}{\rho s}$$

In this investigation the thermal diffusivity has been calculated for the mixtures for which the thermal conductivity was determined, and also for the marble.

4. *Method of Measuring Conductivity.*—It is evident that the quantities required for the determination of thermal conductivity are Q, the quantity of heat passing under steady flow conditions at right angles through a surface of predetermined area S, and the quantity $\frac{t_2 - t_1}{l}$, or temperature gradient. For poor heat conductors, such as concrete and marble, the method most commonly employed for the measurement of the quantities has been the "plate" or "wall" method. In this method an essential condition is to have steady flow through a flat plate of uniform thickness, and the lines of flow at right angles to the faces of the plate; this condition is practically realized for the middle part of an extended disk. The heat may be generated electrically in a flat coil, and the quantity of heat can be easily calculated from the electrical energy consumed. Another method of obtaining the quantity of heat Q is to absorb the transmitted heat in a water jacket, and measure the rise in temperature of the water. Still another method is that used by Lees and Charlton* in which the transmitted heat was radiated from a standard plate under constant conditions, the constants for this radiated heat having been determined by a separate experiment. The method of determining thermal conductivity which

* Phil. Mag. No. 5, Vol. 41, p. 495, June, 1898.

has been used in this investigation can be described as the "cylinder method." It is the same general method as was used in the determination of the thermal conductivity of fire-clay made in this laboratory in 1909.* A long cylinder of the substance is used, and the heat is generated electrically in a coil placed in a hole running axially through the cylinder. Near the ends of the cylinder the flow of heat is, of course, not radial, but for some length near the middle of a long cylinder we can assume radial flow. Experiments show that this assumption is justified. The amount of heat generated per unit length of the middle part of the cylinder is easily calculated from measurements of the electromotive force, E, and the current, I, flowing in the coil.

To measure the temperature gradient of the heat flow, small "probing" holes are placed in the cylinder, parallel to the axis, and extending from one end to the middle of the cylinder where the temperature is to be measured. In most of the cylinders used, there were three such holes, one near the coil hole along the axis, one near the outer surface of the cylinder, and one about half way between. The temperatures can be read by thermocouples placed in these holes. Then, knowing the radial distances r_1 and r_2, and the corresponding temperatures t_1 and t_2, the temperature gradient is determined directly. Fig. 1 shows the arrangement and location of the coil and the thermocouples.

Fourier's equation for the stationary flow of heat becomes, in the case of a long cylinder, with source along the axis,

$$Q = \frac{2 \pi k l}{\log r_2/r_1} (t_1 - t_2) T \quad \dagger$$

The equation for the thermal conductivity then becomes

$$k = \frac{Q}{2 \pi l (t_1 - t_2) T} \log \frac{r_2}{r_1}$$

All the quantities on the right-hand side of this equation can be directly measured, and thus the absolute thermal conductivity can be determined.

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* Thermal Conductivity of Fire Clay at High Temperatures." Univ. of Ill. Eng. Exp. Sta. Bul. No. 36, 1909.

† Ingersoll and Zoebel, "The Mathematical Theory of Heat Conduction," p. 27.

5. *Method of Measuring Diffusivity.*—Diffusivity has already been defined as thermal conductivity divided by the product of specific heat and density. To determine the diffusivity of a material it is, therefore, necessary to determine the specific heat and the density as well as the conductivity.

In the present investigation the ''method of mixture'' with water was used to determine the specific heat. The concrete was broken into pieces containing from 1½ to 2 cubic inches and about 300 grams of these pieces were used in each determination. These were heated to about 100 deg. C. for four hours in an oven to be sure that all portions were at a uniform temperature.

To determine the specific gravity large pieces of the dried concrete were covered with a thin coating of paraffin, and weighed in air, and in water.

III. Composition and Preparation of the Concrete Cylinders

6. *Materials and Proportions Used.*—In making the concrete test cylinders, "Universal" portland cement was used. The sand and gravel were of dolomitic limestone from a pit at Attica, Indiana. The specific gravity of the stone was about 2.65. The gravel weighed 99 pounds per cubic foot, loose, and the sand 110 pounds per cubic foot. Sieve analyses were made of the sand and gravel, using "Tyler standard series." The results of the analyses are shown in Table 1. The sand was coarse and well suited for making concrete, and the gravel was well graded.

After consideration of various mixtures of sand and gravel, the proportion of 55 per cent sand to 45 per cent gravel, by weight, was chosen, though the proportioning was actually done by loose volumes. These proportions lie between the coarser mixtures that are frequently used and the mixtures that have larger percentages of sand; they gave an easily worked mixture. The aggregate of this mixture had a weight of 125 lbs. per cubic foot, and this corresponds to 25 per cent of voids.

Three consistencies were used in the concrete mixtures, the normal consistency, which will be referred to as 100 per cent water content, and two others, with 10 per cent and 20 per cent additional water, respectively, which will be referred to as 110 per cent and 120 per cent water content. The normal consistency was such that freshly molded concrete in the form of a cylinder 8 inches in diameter by 12 inches long, with a 1:4 mix, would slump ½ inch to 1 inch when the form was removed.

In Table 2 will be found the proportions of the different constituents for the mixtures tested: these proportions are stated on a volume basis. In the table the quantity of each constituent in one cubic foot of the mixed concrete is also given.

The forms were removed from the cylinders after the concrete had set 24 hours. The cylinders were then stored in damp sand for two weeks, and afterwards removed to a dry room. They were all thoroughly dry when tested. The appearance of the cross sections of broken concrete cylinders is shown in Fig. 2.

TABLE 1

SIEVE ANALYSIS OF SAND AND GRAVEL USED IN CONCRETE CYLINDERS TESTED

(Percentages are based upon weight)

Sieve Size	Size of Square Opening		Per Cent of Sample Coarser than a Given Sieve	
	In.	Mm.	Sand	Gravel
100 mesh	0.0058	0.147	99.0	100.0
48 mesh	0.0116	0.295	97.1	100.0
28 mesh	0.0232	0.59	81.6	100.0
14 mesh	0.046	1.17	52.0	100.0
8 mesh	0.093	2.36	33.6	100.0
4 mesh	0.185	4.70	8.6	99.4
⅜ in.	0.37	9.4	0.0	97.2
¾ in.	0.75	18.8	0.0	49.8
1.5 in.	1.5	38.1	0.0	0.0

TABLE 2

COMPOSITION OF CONCRETE MIXTURES USED IN CYLINDERS TESTED

Mixture Cement: Aggregate	Ratios Cement: Sand: Gravel	Relative Water Content Per Cent	Volumes in Cu. Ft.			
			Cement Cu. Ft.	Sand Cu. Ft.	Gravel Cu. Ft.	Water Cu. Ft.
1:2	1-1.2-1.1	100	0.50	0.620	0.567	0.282
		110				0.310
		120				0.338
1:3	1-1.9-1.7	100	0.33	0.62	0.567	0.225
		110				0.248
		120				0.270
1:4	1-2.4-2.3	100	0.25	0.62	0.567	0.196
		110				0.216
		120				0.235
1:5	1-3.1-3.0	100	0.20	0.62	0.567	0.176
		110				0.194
		120				0.211
1:7	1-4.3-4.0	110	0.143	0.62	0.567	0.171
		120				0.186
1:9	1-5.6-5.1	110	0.111	0.62	0.567	0.160
		120				0.175
"Neat"		100	1.00			0.384
		110				0.423

IV. Testing Procedure

7. *Description of Test Specimens and Apparatus Used.*—The cylinders were 24 inches long and 7½ inches in diameter. The central hole for the heating coil was 1½ inches in diameter. The holes for inserting the thermocouples were made by placing 5/32-inch rods in the fresh concrete parallel to the axis, and at different radial distances. A section of the cylinder and the heating coil is shown in Fig. 1.

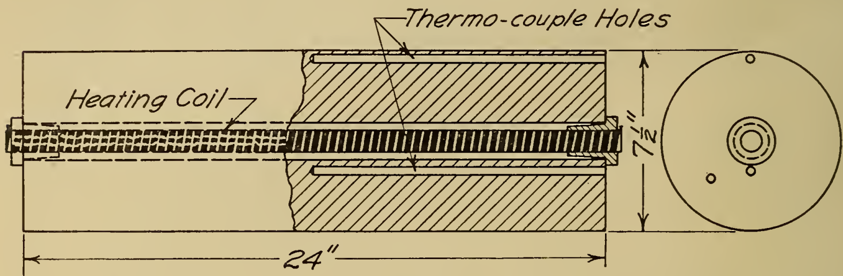

Fig. 1. Sectional and End Views of Test Cylinder, Showing Location of Heating Coil and Thermocouples

The heating coils were made by winding "Chromel C"* ribbon 0.25 inch by 0.025 inch on hard porcelain insulator tubes 24 inches long. In order to center the heating coils, tapered collars for the ends were made of portland cement and plaster of Paris. The outer surfaces of the concrete cylinders were covered with a very thin coat of plaster of Paris to make the emissivity uniform over the surface of the cylinder. The current for the heating coil was supplied by a motor-generator set equipped with a General Electric special voltage regulator, the motor of the set being driven by the alternating current from the University mains, which is of fairly constant voltage. The regulator kept the voltage of the 110 D.C. generator constant to within less than one-half of one per cent. It was found necessary to heat the cylinders from 14 to 16 hours before the temperature became constant so that observations could be taken. A Thwing thermocouple recorder

* This is a nickel-chromium alloy resistance metal made by the Hoskins Manufacturing Company of Detroit, Michigan.

was used to indicate when a steady condition of temperature was reached.

Fig. 3 shows the method of insulating the hot junction of the thermocouple and centering it in the hole; the outside glass protecting tube fitted closely in the holes in the cylinder. Copper-constantan thermocouples were used, and were calibrated by first of all determining the readings at three fixed temperatures, the boiling point of water,

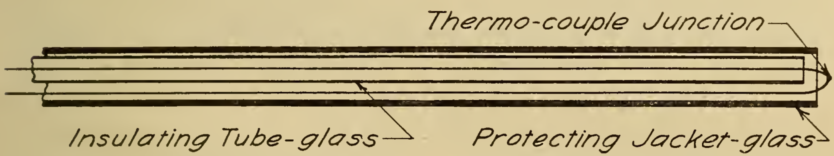

FIG. 3. METHOD OF INSULATING AND CENTERING HOT JUNCTION OF THERMOCOUPLES

the boiling point of napthalene, and the melting point of lead. These three points having been determined, the complete calibration curve for each couple was drawn by comparison with the calibration curve for a standard thermocouple, that had been carefully calibrated. A Wolff potentiometer was used to measure the electromotive force. The general arrangement of the apparatus and circuits are shown in Figs. 4 and 5.

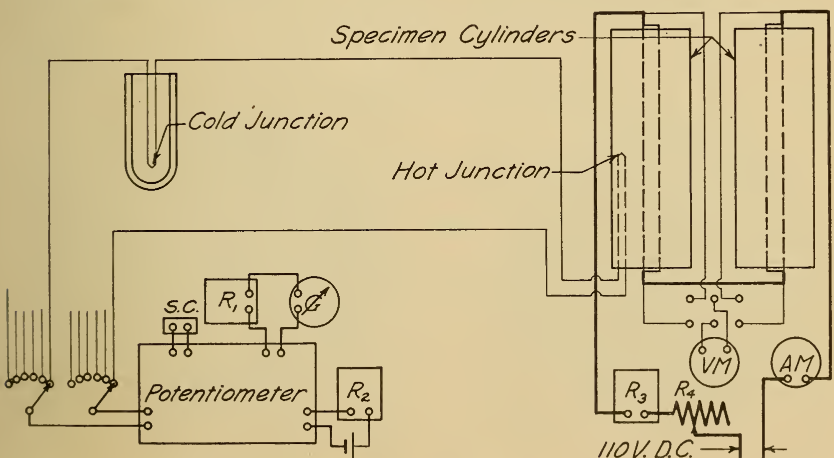

FIG. 4. GENERAL ARRANGEMENT OF APPARATUS AND ELECTRICAL CIRCUITS

8. *Testing Procedure.*—Temperature readings were taken for most of the cylinders at three radial distances from the axis. On the first tests a thermocouple was used in each hole and temperatures were taken simultaneously, but it was afterwards found that one thermocouple could be used, and changed from one hole to the other, without affecting the accuracy of the observations. Temperature readings were taken over a range of five centimeters axial length at the middle of the cylinder. Preliminary tests had shown that for this portion of the cylinder there was practically no variation in temperature parallel to the axis; that is, the flow of heat was truly radial through this mid-portion of the cylinder. The current through the heating coils and the potential differences were read at the beginning and at the end of each set of observations. In most of the determinations a length of heating coil of 59 cm. was used, but for a few cases the length was 57.5 cm. Before taking any test temperature readings the cylinders were first given a preliminary heating to a temperature of over 100 deg. C. in order to dry them out; this was found to be necessary in order to obtain consistent readings.

After the tests were completed the cylinders were broken as near the middle as possible and the radial distances of the thermocouple holes from the cylinder axes were measured. In calculating the thermal conductivity, these measured radial distances were used, with the corresponding temperatures.

Fig. 2 shows sectional views of the cylinders when broken, and the probing holes for measuring the temperature can be seen. Fig. 6 shows a collection of cylinders which were tested. Results of experiments on fifty-one concrete cylinders are given in the tables.

9. *Tests on a Marble Cylinder.*—In addition to the tests on the concrete cylinders, some tests were made on a cylinder of marble, of similar dimensions. White Alabama marble was used, the sample having been purchased from the Peoria Marble Works of Peoria, Illinois. The grain of this marble was of a fine sugary texture and the specimen is described as being of a "very good grade" of marble. Chemical analysis showed that it was composed principally of calcium carbonate, with a small amount of magnesium carbonate. The tests were made both for thermal conductivity and for diffusivity. Before testing, in order to free the marble from moisture, it was heated to 130 deg. C. in a large oven for four hours. In carrying out the con-

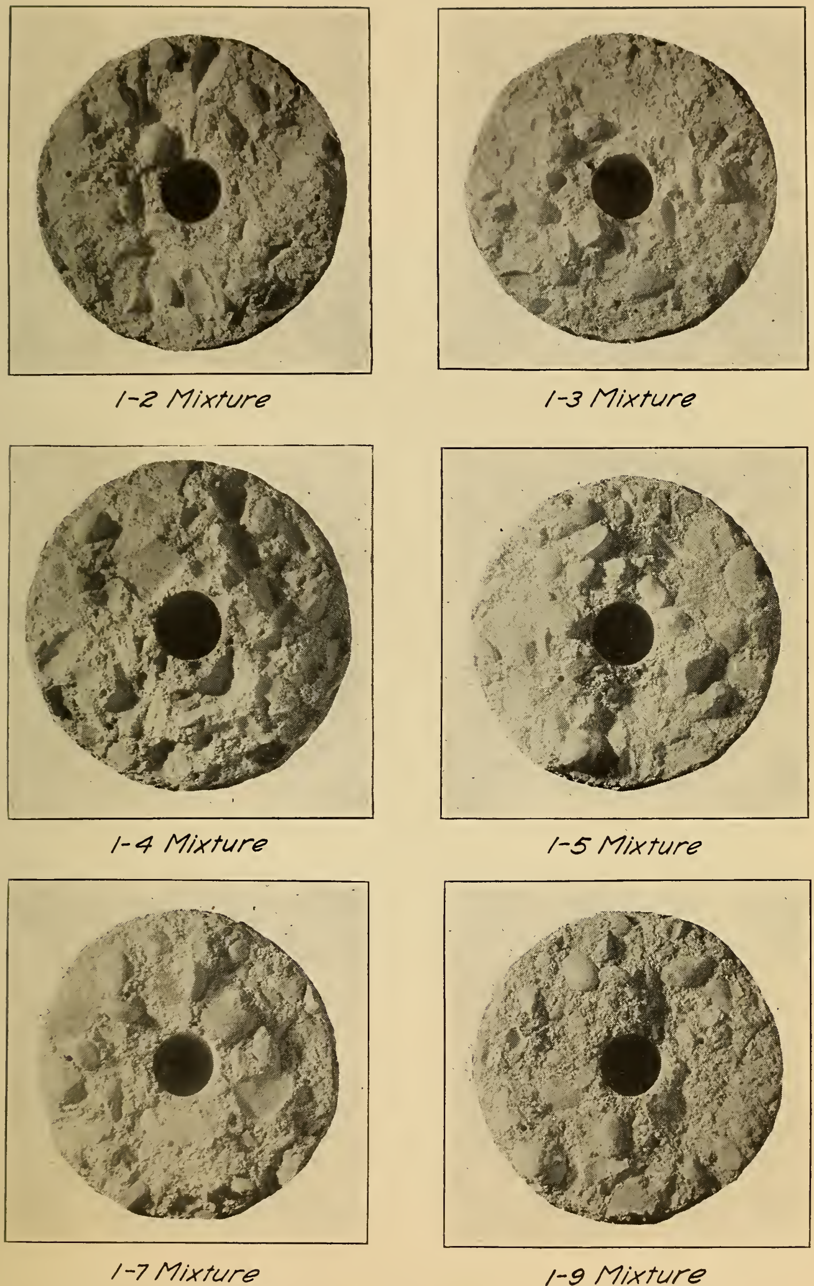

Fig. 2. Cross-sectional Views of Broken Concrete Cylinders

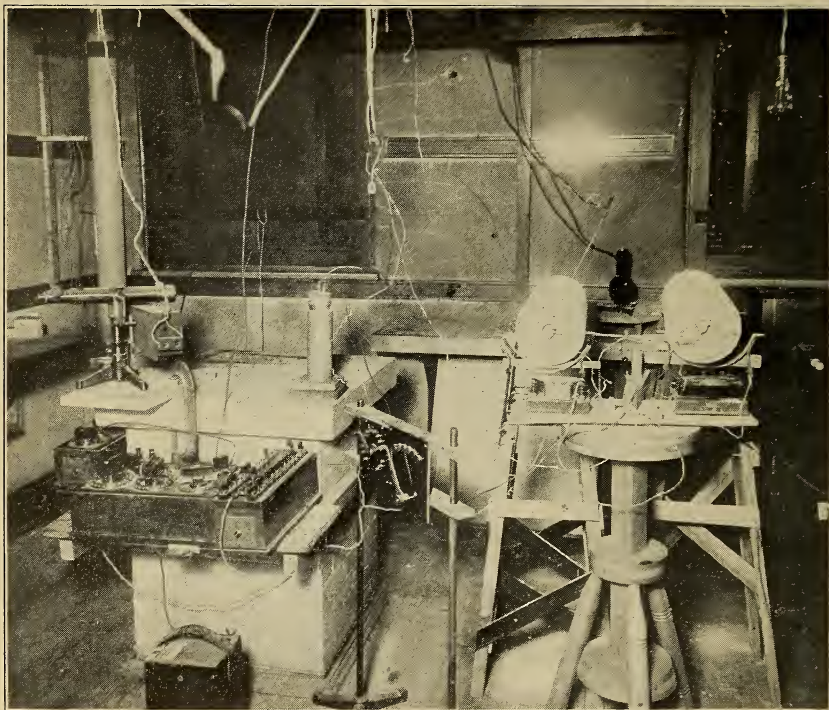

Fig. 5. General View of Apparatus

FIG. 6. GENERAL VIEW OF BROKEN TEST CYLINDERS

ductivity tests the cylinder was first heated to about 50 deg. C. and readings taken; the temperature was then increased each day, and observations made, until a temperature of about 200 deg. C. was reached; the specimen was then allowed to cool, and was again tested in the same manner. At about 235 deg. C. the cylinder cracked in several places, and observations were discontinued. The results of the conductivity tests are given in Table 11; the mean values for the conductivity are given in Table 13.

For purposes of comparison, in Table 3 are given figures for specific gravity, specific heat, thermal conductivity, and diffusivity for the sample tested, and also for another sample of a somewhat similar marble, the values given in the latter case having been taken from results already published by Pierce and Wilson.*

TABLE 3

PROPERTIES OF MARBLE

	Pierce and Wilson's "American White"	"Alabama White"
Specific gravity	2.72	2.71
Specific heat	0.214	0.213
Thermal conductivity	0.00596	0.00614
Diffusivity	0.0102	0.0106

* Proc. Am. Acad. Arts and Sciences, Vol. 36, 1900.

V. Results of Observations and Determinations

10. *Explanation of Tables.*—The results of the observations and calculations are shown in Tables 4 to 11. Tests were made on fifty-one concrete cylinders, including three cylinders of "neat" cement, and on one cylinder of "White Alabama" marble. The first column gives the identification mark for the cylinder; the second column gives the "relative water content" as defined in Section III, page 12; the third column gives the number of days, at the time of test, since the cylinder was cast; the fourth and fifth columns give the radial distances r_1 and r_2 of the probing holes at which the temperatures t_1 and t_2, given in the eighth and ninth columns, were measured; the sixth and seventh columns give respectively the current I in amperes, and the electromotive force E in volts of the heating coil, for calculating the heat Q; the tenth and eleventh columns give the values of k, the thermal conductivity in "c.g.s." and "British engineering" units as defined in Section II, page 7; the material of the cylinder is indicated in the caption. The proportions of the concrete mixtures are given in Table 2.

In Table 12 are given values for densities, specific heats, conductivities, and diffusivities, for the different mixtures of concrete, and for the marble. These values for concrete are given for one relative water content only, namely, 110 per cent; it was considered that thus good average values would be obtained, and that in any case the diffusivity would not show much variation with variation of the relative water content.

In calculating the diffusivities the conductivities determined for a range of temperature of from 100 deg. C. to 200 deg. C. were used. This was done because it was felt that these results were more reliable, both on account of the larger number of readings taken over this range, and because the readings were somewhat more consistent, owing to the larger temperature differences.

TABLE 4

THERMAL CONDUCTIVITY OF NEAT CEMENT

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
1H	100	28	3.493	6.055	15.67	27.30	253.7	152.5	0.00150	0.363
			3.493	9.508			253.7	91.5	0.00170	0.411
1H	100	120	3.493	6.055	17.02	29.7	345.7	212.1	0.00135	0.327
			6.055	9.508			212.1	123.0	0.00165	0.399
			3.493	9.508			345.7	123.0	0.00147	0.356
1H	100	150	3.493	6.055	7.48	12.15	91.0	67.6	0.00138	0.334
			6.055	9.508			67.6	49.0	0.00142	0.344
			3.493	9.508			91.0	49.0	0.00140	0.339
3H	110	28	2.244	4.958	13.99	24.40	286.6	148.8	0.00126	0.305
			2.244	8.799			286.6	89.2	0.00153	0.370
4H	110	28	2.990	6.378	13.99	25.00	217.1	112.9	0.00164	0.397

TABLE 5

THERMAL CONDUCTIVITY OF CONCRETE

Mixture 1:2

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
1E	110	28	2.394	4.811	16.41	26.10	197.2	138.8	0.0033	0.80
			2.394	8.662			197.2	103.4	0.0038	0.92
1E	110	120	2.394	4.811	19.00	32.95	321.8	229.4	0.0031	0.75
2E	110	28	2.161	6.131	16.37	28.40	239.3	145.3	0.0033	0.80
			6.131	9.255			145.3	104.9	0.0031	0.75
			2.161	9.255			239.3	104.9	0.0033	0.80
2E	110	120	2.161	6.131	19.00	33.35	354.2	210.8	0.0031	0.75
2E	110	140	2.161	6.131	7.52	12.21	76.4	56.3	0.0031	0.75
			6.131	9.255			56.3	48.0	0.0029	0.70
			2.161	9.255			76.4	48.0	0.0030	0.73
3E	100	28	2.313	7.390	15.64	24.80	194.2	115.6	0.0037	0.90
			2.313	7.567			194.2	113.9	0.0037	0.90
			2.313	7.390	16.18	25.25	221.0	132.5	0.0035	0.85
			2.313	7.567			221.0	128.2	0.0034	0.82
3E	100	120	2.313	7.390	17.02	29.70	265.4	151.1	0.0034	0.82
			2.313	7.567			265.4	142.4	0.0032	0.77
3E	100	140	2.313	7.390	7.55	12.39	68.7	49.5	0.0037	0.90
			2.313	7.567			68.7	48.9	0.0036	0.87
3E	100	150	2.313	7.390	19.13	32.80	334.7	175.4	0.0030	0.73
			2.313	7.567			334.7	174.3	0.0031	0.75
4E	120	28	4.860	6.372	16.18	28.00	170.4	137.4	0.0024	0.58
			6.372	9.270			137.4	110.2	0.0040	0.97
			4.860	9.270			170.4	110.2	0.0031	0.75
5E	110	28	3.978	9.297	16.36	26.00	174.7	105.2	0.0033	0.80
5E	110	120	4.423	9.297	15.08	25.61	155.8	107.8	0.0038	0.92
			3.978	9.297			170.1	107.8	0.0034	0.82
6E	100	28	2.528	7.105	16.79	27.80	245.2	151.4	0.0033	0.80
			2.528	7.936			245.2	134.1	0.0031	0.75
			2.528	7.105	16.79	28.30	260.0	161.4	0.0035	0.85
			2.528	7.936			260.0	143.1	0.0030	0.73
6E	100	120	2.528	7.105	15.09	26.35	220.9	140.5	0.0034	0.82
			2.528	7.936			220.9	121.8	0.0030	0.73
7E	100	28	3.003	5.493	16.18	28.25	189.4	144.7	0.0040	0.97
			3.003	9.123			189.4	112.9	0.0043	1.04

Table 6

Thermal Conductivity of Concrete

Mixture 1:3

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
1D	110	28	2.594	6.776	15.80	24.85	175.4	115.1	0.0040	0.97
			2.594	6.776	19.72	30.35	289.6	171.5	0.0031	0.75
			6.776	9.196			171.5	132.5	0.0030	0.73
			2.594	9.196			289.6	132.5	0.0031	0.75
2D	100	28	2.467	4.904	15.80	27.50	196.2	138.7	0.0034	0.82
			2.467	8.713			196.2	104.1	0.0038	0.92
			2.467	4.904	19.75	34.55	312.5	217.3	0.0032	0.77
			4.904	8.713			217.3	155.2	0.0041	0.99
			2.461	8.713			312.5	155.2	0.0035	0.85
3D	110	28	2.420	7.097	15.09	23.45	159.1	107.5	0.0048	1.16
			2.420	7.097	16.00	26.00	199.8	133.0	0.0044	1.06
			2.420	9.024			199.8	105.7	0.0038	0.92
4D	110	28	2.220	8.841	15.10	26.15	185.2	98.2	0.0040	0.97
			2.220	4.197	16.00	27.50	222.9	168.9	0.0034	0.82
			4.197	8.841			168.9	116.1	0.0040	0.97
			2.220	8.841			222.9	116.1	0.0037	0.90
5D	110	28	2.307	5.852	17.12	29.75	234.7	164.8	0.0044	1.06
			5.852	9.235			164.8	126.2	0.0039	0.94
			2.307	9.235			234.7	126.2	0.0042	1.01
5D	110	120	2.307	5.852	14.94	24.00	181.7	121.7	0.0036	0.87
			5.852	9.235			121.7	94.0	0.0038	0.92
			2.307	9.235			181.7	94.0	0.0037	0.90
5D	110	140	2.307	5.852	7.46	12.02	72.0	54.0	0.0031	0.75
			5.852	9.235			54.0	47.0	0.0039	0.94
			2.307	9.235			72.0	47.0	0.0033	0.80
6D	110	28	4.478	9.252	17.14	26.55	168.4	120.5	0.0044	1.06
			2.474	9.252			228.1	120.5	0.0036	0.87
6D	110	120	2.474	4.478	14.94	24.40	169.5	135.9	0.0043	1.04
7D	120	28	2.535	6.225	16.43	28.45	226.5	147.1	0.0034	0.82
			6.225	9.255			147.1	118.6	0.0037	0.90
			2.535	9.255			226.5	118.6	0.0036	0.87
7D	120	120	2.535	6.225	13.83	24.00	179.3	121.1	0.0033	0.80
			6.225	9.255			121.1	95.1	0.0035	0.85
			2.535	9.255			179.3	95.1	0.0033	0.80
7D	120	140	2.535	6.225	7.51	12.25	70.8	54.5	0.0033	0.80
			6.225	9.255			54.5	46.6	0.0032	0.77
			2.535	9.255			70.8	46.6	0.0032	0.77
8D	100	28	2.253	4.953	16.17	25.60	188.8	138.9	0.0042	1.01
			4.953	7.819			138.9	110.1	0.0042	1.01
			2.253	7.819			188.8	110.1	0.0042	1.01
9D	100	28	2.360	4.230	16.77	28.80	248.9	194.8	0.0034	0.82
			4.230	9.131			194.8	127.7	0.0036	0.87
			2.360	9.131			248.9	127.7	0.0036	0.87
			2.360	4.230	16.79	29.10	259.8	200.1	0.0031	0.75
			4.230	9.131			200.1	132.2	0.0038	0.92
			2.360	9.131			259.8	132.2	0.0033	0.80
9D	100	120	2.360	4.230	13.83	24.65	183.8	145.0	0.0034	0.82
			4.230	9.131			145.0	103.6	0.0042	1.01
			2.360	9.131			183.8	103.6	0.0038	0.92
9D	100	140	2.360	4.230	7.73	12.50	71.9	60.5	0.0033	0.80
			4.230	9.131			60.5	46.9	0.0036	0.87
			2.360	9.131			71.9	46.9	0.0035	0.85
11D	120	120	2.653	5.539	12.88	21.90	143.6	103.5	0.0033	0.80
			2.653	9.073			143.6	85.0	0.0038	0.92
			2.653	5.539	14.56	25.00	189.9	137.0	0.0033	0.80
			2.653	9.073			189.9	105.9	0.0034	0.82
			2.653	5.539	13.83	23.60	173.7	126.5	0.0033	0.80
			2.653	9.073			173.7	98.5	0.0035	0.85
11D	120	140	2.653	5.539	7.26	11.77	66.1	52.8	0.0031	0.75
			2.653	9.073			66.1	46.1	0.0034	0.82
			2.653	9.073	10.17	17.10	106.2	65.6	0.0034	0.82
			2.653	9.073	13.96	23.90	176.9	97.5	0.0033	0.80
			2.653	5.539	18.19	31.00	268.0	181.6	0.0031	0.75
			2.653	9.073			268.0	124.4	0.0031	0.75
			2.653	5.539	18.26	31.10	283.5	195.0	0.0031	0.75
			2.653	9.073			283.5	139.6	0.0031	0.75

TABLE 7

THERMAL CONDUCTIVITY OF CONCRETE

Mixture 1:4

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engi-neering
1C	110	28	2.616	5.038	15.28	24.05	161.4	119.2	0.0037	0.90
			5.038	8.293			119.2	94.2	0.0047	1.14
			2.616	8.293			161.4	94.2	0.0041	0.99
			2.616	5.038	19.81	32.61	322.5	240.5	0.0033	0.80
			5.038	8.293			240.5	168.8	0.0029	0.70
			2.616	8.293			322.5	168.8	0.0031	0.75
2C	100	28	2.498	4.406	15.58	26.75	176.8	136.2	0.0038	0.92
			4.406	6.693			136.2	111.7	0.0046	1.11
			2.498	6.693			176.8	111.7	0.0041	0.99
3C	110	28	2.440	6.455	15.61	24.1	192.9	116.9	0.0031	0.75
			6.455	7.395			116.9	107.8	0.0036	0.87
			2.440	7.395			192.9	107.8	0.0032	0.77
3C	110	120	2.440	6.455	15.00	25.95	199.6	133.8	0.0037	0.90
			6.455	7.395			133.8	121.4	0.0028	0.68
			2.440	7.395			199.6	121.4	0.0036	0.87
3C	110	140	2.440	6.455	7.52	12.21	65.2	50.8	0.0040	0.97
			2.440	7.395			65.2	50.1	0.0043	1.04
3C	110	150	2.440	6.455	19.14	32.81	317.3	196.0	0.0036	0.87
4C	110	28	2.639	3.679	16.41	26.00	198.3	177.8	0.0044	1.06
			3.679	9.469			177.8	104.1	0.0035	0.85
			2.639	9.464			198.3	104.1	0.0037	0.90
5C	110	28	2.700	5.852	16.41	28.50	207.7	148.0	0.0039	0.94
			2.700	9.125			207.7	122.4	0.0043	1.04
6C	100	28	5.569	9.103	15.90	27.55	158.5	122.1	0.0037	0.90
6C	100	120	5.569	9.103	14.96	25.9	142.4	108.5	0.0036	0.87
			4.588	9.103			159.9	108.5	0.0033	0.80
7C	100	28	2.494	6.998	15.84	27.85	234.2	143.2	0.0032	0.77
			6.998	8.725			143.2	125.5	0.0035	0.85
			2.494	8.725			234.2	125.5	0.0033	0.80
7C	100	120	2.494	6.998	14.93	26.20	216.2	128.9	0.0030	0.73
			2.494	8.725			216.2	118.5	0.0032	0.77
8C	120	28	2.232	5.966	15.21	26.35	232.5	147.8	0.0030	0.73
			5.966	9.467			147.8	114.0	0.0035	0.85
			2.232	9.467			232.5	114.0	0.0032	0.77
8C	120	120	2.232	5.966	14.93	26.05	229.0	136.8	0.0028	0.68
10C	120	28	2.563	5.588	16.01	27.35	238.6	152.9	0.0026	0.63
			5.588	9.075			152.9	113.8	0.0035	0.85
			2.563	9.075			238.6	113.8	0.0029	0.70
10C	120	120	2.563	5.588	17.61	31.15	273.4	186.9	0.0033	0.80
			5.588	9.075			186.9	133.6	0.0033	0.80
			2.563	9.075			273.4	133.6	0.0033	0.80
			2.563	9.075	14.92	26.25	216.2	118.3	0.0034	0.82
10C	120	140	2.563	5.588	7.53	12.31	66.2	56.8	0.0051	1.23
			5.588	9.075			56.8	47.2	0.0031	0.75
			2.563	9.075			66.2	47.2	0.0041	0.99

TABLE 8

THERMAL CONDUCTIVITY OF CONCRETE

Mixture 1:5

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engi-neering
1B	110	28	2.531	8.890	72.3	7.12	244.7	128.0	0.0035	0.84
1B	110	28	2.531	8.890	90.0	8.71	360.1	176.4	0.0034	0.82
3B	110	28	2.651	3.298	12.05	19.00	116.0	105.1	0.0037	0.90
			3.298	7.595			105.0	80.8	0.0041	0.99
			2.651	7.595			116.0	80.8	0.0045	1.09
4B	110	28	2.610	6.014	12.05	20.95	101.2	83.4	0.0035	0.85
			2.610	8.510			101.2	71.5	0.0040	0.97
5B	110	28	2.512	4.666	11.83	20.30	122.2	96.7	0.0037	0.90
			4.666	8.522			96.7	75.3	0.0035	0.85
			2.512	8.522			122.2	75.3	0.0033	0.80
			2.512	4.666	19.80	29.65	290.8	233.6	0.0041	0.99
			4.666	8.522			233.6	170.9	0.0036	0.87
			2.512	8.522			290.8	170.9	0.0039	0.94
			2.512	4.666			154.6	115.8	0.0041	0.99
			4.666	8.522			115.8	96.2	0.0040	0.97
			2.512	8.522			154.6	96.2	0.0040	0.97
6B	100	28	2.474	6.064	16.02	25.4	210.7	146.7	0.0039	0.94
			6.064	9.181			146.7	114.5	0.0034	0.82
			2.474	9.181			210.7	114.5	0.0036	0.87
6B	100	120	2.474	6.064	14.93	26.10	211.0	138.8	0.0032	0.77
			6.064	9.181			138.8	110.0	0.0037	0.89
			2.474	9.181			211.0	110.0	0.0034	0.82
7B	120	28	2.308	7.043	15.08	26.70	235.3	129.6	0.0028	0.68
			7.043	8.550			129.6	116.3	0.0038	0.92
			2.308	8.550			235.3	116.3	0.0029	0.70
7B	120	120	2.308	7.043	14.92	26.01	232.9	126.3	0.0027	0.65
			7.043	8.550			126.3	110.6	0.0031	0.75
			2.308	8.550			232.9	110.6	0.0027	0.65
			2.308	7.043	7.73	12.54	80.3	54.8	0.0028	0.68
			7.043	8.550			54.8	49.0	0.0021	0.51
			2.308	8.550			80.3	49.0	0.0027	0.65
7B	120	150	2.308	7.043	19.14	32.70	375.5	188.9	0.0025	0.61
			7.043	8.550			188.9	157.7	0.0025	0.61
			2.308	8.550			375.5	157.7	0.0025	0.61
8B	120	28	4.788	5.586	15.09	26.40	163.6	154.3	0.0043	1.04
			5.586	9.288			154.3	114.4	0.0033	0.80
			4.788	9.288			163.6	114.4	0.0034	0.82
8B	120	120	4.788	5.586	14.94	25.91	162.9	145.7	0.0025	0.60
			5.586	9.288			145.7	107.4	0.0034	0.80
			4.788	9.288			162.9	107.4	0.0030	0.73
9B	120	28	2.304	6.754	15.64	27.45	238.5	136.8	0.0029	0.70
			6.754	9.187			136.8	109.0	0.0031	0.75
			2.304	9.187			238.5	109.0	0.0030	0.73
9B	120	120	2.304	6.754	17.61	30.61	293.0	162.1	0.0028	0.68
			6.754	9.187			162.1	133.4	0.0036	0.87
			2.304	9.187			293.0	133.4	0.0030	0.73
9B	120	140	2.304	6.754	7.73	12.60	78.2	51.7	0.0026	0.63
			6.754	9.187			51.7	46.3	0.0035	0.85
			2.304	9.187			78.2	46.3	0.0027	0.65

TABLE 9

THERMAL CONDUCTIVITY OF CONCRETE

Mixture 1:7

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
1F	110	28	5.224	7.641	16.72	27.15	167.4	137.8	0.0036	0.87
			3.395	7.641			190.1	137.8	0.0043	1.04
2F	110	28	4.599	8.178	16.71	28.85	178.4	128.8	0.0036	0.87
3F	120	28	2.468	5.463	15.76	24.40	216.3	142.0	0.0027	0.65
			5.463	7.058			142.0	119.4	0.0028	0.68
			2.468	7.058			216.3	119.4	0.0027	0.65
3F	120	120	5.463	7.058	15.61	27.10	152.4	130.3	0.0032	0.77
4F	120	28	5.724	8.096	15.76	27.10	148.8	117.5	0.0031	0.75
			3.787	8.096			173.7	117.5	0.0031	0.75
5F	110	28	5.190	8.772	15.55	23.25	141.9	114.1	0.0044	1.06
			3.050	8.772			194.3	114.1	0.0031	0.75
5F	110	120	3.050	5.190	15.62	27.30	196.0	155.0	0.0037	0.90
			5.190	8.772			155.0	120.6	0.0043	1.04
			3.050	8.772			196.0	120.6	0.0040	0.97
5F	110	140	3.050	5.190	7.47	12.15	65.0	55.5	0.0041	0.99
			5.190	8.772			55.5	48.3	0.0043	1.04
			3.050	8.772			65.0	48.3	3.0037	0.90
6F	120	28	2.296	6.491	15.70	27.20	224.7	148.7	0.0037	0.90
			6.491	9.174			148.7	110.8	0.0026	0.63
			2.296	9.174			224.7	110.8	0.0033	0.80

TABLE 10

THERMAL CONDUCTIVITY OF CONCRETE

Mixture 1:9

Cylinder Mark	Relative Water Content Per Cent	Age Days	r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
1G	110	28	2.362	4.828	16.1	25.3	234.0	155.4	0.0024	0.58
2G	110	28	3.642	5.232	16.08	27.70	190.7	161.0	0.0035	0.85
			5.232	7.976			161.0	126.6	0.0035	0.85
			3.642	7.976			190.7	126.6	0.0035	0.85
2G	110	120	3.642	5.232	15.38	26.30	172.4	150.3	0.0044	1.06
			5.232	7.976			150.3	119.6	0.0037	0.90
			3.642	7.976			172.4	119.6	0.0040	0.97
3G	110	28	3.315	5.595	16.00	24.00	194.9	150.8	0.0030	0.73
			5.595	7.495			150.8	130.1	0.0035	0.85
			3.315	7.495			194.9	130.1	0.0031	0.75
3G	110	120	3.315	7.495	15.27	26.65	174.5	118.5	0.0038	0.92
3G	110	150	3.315	5.595	7.55	12.44	58.8	53.4	0.0060	1.45
			5.595	7.495			53.4	50.0	0.0054	1.30
			3.315	7.495			58.8	50.0	0.0058	1.41
3G	110	150	3.315	7.495	19.13	32.65	259.4	172.5	0.0038	0.92
4G	110	28	4.589	4.978	15.97	26.50	170.0	164.2	0.0038	0.92
			4.978	7.611			164.2	133.4	0.0038	0.92
			4.587	7.611			170.0	133.4	0.0038	0.92
4G	110	120	4.589	4.978	15.27	26.85	159.9	154.6	0.0042	1.02
			4.978	7.611			154.6	121.7	0.0035	0.85
			4.589	7.611			159.9	121.7	0.0036	0.87
5G	120	28	2.316	5.234	15.55	23.20	228.8	162.8	0.0029	0.70
			5.234	9.134			162.8	112.9	0.0026	0.63
			2.316	9.134			228.8	112.9	0.0027	0.65

TABLE 11

THERMAL CONDUCTIVITY OF "ALABAMA WHITE" MARBLE

r_1 cm.	r_2 cm.	I Amp.	E Volts	t_1 deg. C.	t_2 deg. C.	k c. g. s. Physical	k British Engineering
2.890	6.401	7.25	11.71	58.7	51.5	0.0063	1.52
6.401	8.911			51.5	48.3	0.0059	1.43
2.890	6.401	9.53	16.10	79.9	67.4	0.0065	1.57
6.401	8.911			67.4	62.3	0.0066	1.60
2.890	8.911			79.9	62.3	0.0066	1.60
2.890	6.401	10.18	17.20	88.6	71.6	0.0055	1.33
6.401	8.911			71.6	65.1	0.0061	1.48
2.890	8.911			88.6	65.1	0.0056	1.36
6.401	8.911	12.87	22.05	101.6	91.5	0.0062	1.50
2.890	6.401			128.4	101.6	0.0055	1.33
2.890	8.911			128.4	91.5	0.0059	1.43
2.890	6.401	13.83	23.50	146.7	114.0	0.0053	1.28
6.401	8.911			114.0	99.9	0.0055	1.33
2.890	8.911			146.7	99.9	0.0052	1.26
2.890	6.401	13.96	24.00	147.9	110.4	0.0048	1.16
6.401	8.911			110.4	96.8	0.0054	1.31
2.890	8.911			147.9	96.8	0.0049	1.19
2.890	6.401	14.58	24.90	160.3	124.1	0.0053	1.28
6.401	8.911			124.1	107.9	0.0050	1.21
2.890	8.911			160.3	107.9	0.0052	1.26
6.401	8.911	18.19	31.11	147.0	119.4	0.0045	1.09
2.890	6.401			219.6	147.0	0.0041	0.99
2.890	8.911			219.6	119.4	0.0042	1.02
6.401	8.911	18.27	31.25	160.4	133.3	0.0047	1.14
2.890	6.401			235.2	160.4	0.0041	0.99
2.890	8.911			235.2	133.3	0.0042	1.02

TABLE 12

DIFFUSIVITY OF CONCRETE AND MARBLE

Mixture	Relative Water Content Per Cent	Density		Conductivity		Specific Heat		Diffusivity	
		gms. per c. c.	lbs. per cu. ft.	c. g. s. Physical	British Engi-neering	Per deg. C.	Per deg. F.	c. g. s. Physical	British Engi-neering
"Neat"	110	1.83	114	0.00147	0.356	0.278	0.153	0.00289	0.0204
1-2	110	2.26	141	0.00344	0.832	0.216	0.119	0.00705	0.0492
1-3	110	2.28	142	0.00379	0.917	0.218	0.121	0.00762	0.0533
1-4	110	2.29	143	0.00352	0.852	0.218	0.121	0.00705	0.0493
1-5	110	2.29	143	0.00323	0.782	0.217	0.120	0.00650	0.0455
1-7	110	2.23	139	0.00384	0.929	0.227	0.126	0.00758	0.0530
1-9	110	2.16	135	0.00352	0.852	0.223	0.124	0.00732	0.0509
Marble		2.71	169	0.00613	1.483	0.213	0.118	0.01059	0.0739

VI. Summary of Results and Conclusions

11. *Summary of Results.*—In the following tables may be found a summary of the detailed observations and calculations contained in Tables 4 to 11.

Table 13 gives the average thermal conductivities of the different mixtures tested, at different temperatures; the values found in the table have been arrived at by collecting and averaging the values given in Tables 4 to 11.

Table 14 gives the average thermal conductivities, at different temperatures, for mixtures in which different amounts of water were

Table 13

Average Thermal Conductivities of Different Mixtures of Concrete, and of Marble, at Different Temperatures
(Averaged from Tables 3 to 10.)

Mixture By Volumes		50° C. to 100° C. 120° F. to 212° F.		100° C. to 200° C. 212° F. to 390° F.		200° C. to 300° C. 390° F. to 570° F.	
Cement: Aggregate	Cement: Sand: Gravel	k c. g. s. Physical	k British Engineering	k c. g. s. Physical	k British Engineering	k c. g. s. Physical	k British Engineering
"Neat"		0.00140	0.339	0.00163	0.394	0.00140	0.339
1-2	1-1.2-1.1	0.00326	0.789	0.00344	0.832	0.00318	0.770
1-3	1-1.9-1.7	0.00335	0.811	0.00379	0.917	0.00318	0.770
1-4	1-2.4-2.3	0.00413	0.995	0.00352	0.852	0.00328	0.794
1-5	1-3.1-3.0	0.00327	0.791	0.00323	0.782	0.00334	0.808
1-7	1-4.3-4.0	0.00400	0.968	0.00384	0.929		
1-9	1-5.6-5.1	0.00574	1.39	0.00352	0.852		
Marble		0.00614	1.49	0.00493	1.19		

Table 14

Variation of Conductivity with Relative Water Content
(Summarized from Tables 4 to 9.)

Mixture	Relative Water Content Per Cent	k in c. g. s. Physical Units			Mixture	Relative Water Content Per Cent	k in c. g. s. Physical Units		
		50° C. to 100° C.	100° C. to 200° C.	200° C. to 300° C.			50° C. to 100° C.	100° C. to 200° C.	200° C. to 300° C.
1:2	100	0.00365	0.00322	0.00320	1:5	100		0.00353	
	110	0.00300	0.00332	0.00310		110	0.00381	0.00380	0.00380
	120		0.00317			120	0.00273	0.00305	0.00270
1:3	100	0.00347	0.00365	0.00340	1:7	110	0.00402	0.00387	
	110	0.00343	0.00391			120		0.00300	
	120	0.00353	0.00345	0.00310	1:9	110	0.00573	0.00359	
1:4	100		0.00357			120		0.00273	
	110	0.00415	0.00373	0.00322					
	120	0.00410	0.00316						

TABLE 15
EFFECT OF AGE ON CONDUCTIVITY
(Summarized from Tables 4 to 9.)

Mixture	Relative Water Content Per Cent	Age Days	k c. g. s. Physical	Mixture	Relative Water Content Per Cent	Age Days	k c. g. s. Physical
1:2	110	28	0.00335	1:5	120	28	0.00330
		120	0.00331			120	0.00297
1:3	110	28	0.00398	1:7	110	28	0.00380
		120	0.00365			120	0.00380
1:4	110	28	0.00376	1:9	110	28	0.00340
		120	0.00337			120	0.00387

used; the values have been arrived at by averaging the values given in Tables 5 to 10.

Table 15 gives the average thermal conductivities for mixtures of different ages. The values have been obtained for only a few of the mixtures, and for one water content only in each case.

12. *General Conclusions.*—From Table 13 it can be seen that the neat cement had a much lower thermal conductivity than any of the sand and gravel concrete mixtures; in fact, the thermal conductivity of the neat cement is scarcely half that of the 1:2 mixture.

In the case of the sand and gravel concrete mixtures, the figures in the table also show that there is practically no difference in thermal conductivity due to the relative "richness" or "leanness" in cement of a mixture, at any rate for the range of temperature of 100 deg. C. to 200 deg. C. The values, as previously noted, are probably more accurate for this range than for lower temperatures, on account of the number and character of the observations.

From the values given in Table 12 for the densities of the various materials it can be calculated that the voids in the sand and gravel concrete mixture range from 16 to 20 per cent; while in the case of the neat cement the percentage of voids is about 42. It seems probable that the proportion of solid material to voids to a large extent determines the conductivity, and this accounts for the fact that the thermal conducivity of the neat cement is so much lower than that of the concrete mixtures, and that the conductivities of the different mixtures are so nearly the same. The same table shows that the thermal conductivity of a stone, like marble, is much greater than that of a concrete mixture.

The figures given in Table 14 appear to indicate that as far as consistency is concerned the maximum thermal conductivity occurs with a relative water content of about 110 per cent; for relative water contents of 100 or 120 per cent the thermal conductivity is generally lower.

From Table 15 it can be seen that age has little if any effect on the thermal conductivity of concrete. If there is any change, there is a slight decrease in thermal conductivity with age, but this is small, and may be due to very small changes in absolute moisture.

Most of the cylinders cracked at temperatures under 300 deg. C., and that fact limited the range of the investigation. In general, the richer mixtures of concrete cracked at lower temperatures than the leaner mixtures. The results indicate that there is very slight, if any, change of conductivity with change of temperature, for concrete; for marble, there is a marked decrease in conductivity with rise of temperature.

In Table 16 are reproduced the results of the experiments of Professor C. L. Norton, to which reference has already been made.*

TABLE 16

EARLIER DETERMINATIONS OF CONDUCTIVITY OF CONCRETE

(From experiments of Professor C. L. Norton.)

Temperatures—degrees C.	Mixture	k--c. g. s. Physical Unit
35	Stone 1-2-5	0.00216
50	Stone 1-2-4	
	Not stamped	0.00110 to 0.00160
50	Cinder 1-2-4	0.00081
200	Stone 1-2-4	0.0021
400	Stone 1-2-4	0.0022
500	Stone 1-2-4	0.0023
1000	Stone 1-2-4	0.0027
1100	Stone 1-2-4	0.0029

Professor Norton's method at the lower temperatures was, as he names it, the "flat-plate" method. For the higher temperatures he used a cylinder of concrete cast about a steel bar which was heated by the passage of a heavy electric current. He gives practically no details, describing his investigation "in outline only." The table indicates a small increase of thermal conductivity with increase of temperature. As the methods employed in his determinations at

* Proceedings of National Association of Concrete Users, Vol. VII, article by C. L. Norton. 1911.

lower temperatures are not the same as those for higher temperatures, the results are not very conclusive. The values of absolute conductivity are considerably lower than those found in the present investigation, but it is impossible to identify the mixtures used.

Willard and Lichty* give for the thermal conductivity of a 1:2:4 concrete mixture the value 8.3 ''per 1-inch thickness per sq. ft. per 1 deg. F.''; this is equivalent to 0.00296 in the c.g.s. physical units. The method of determination employed was a ''hot-air box method,'' a method specially useful for their purpose in testing materials used for the walls of buildings.

From the present investigation, for the more commonly used concrete mixtures, that is, those with proportions of cement to aggregate of 1:3 to 1:7, the following average values of thermal conductivity and thermal diffusivity appear established: for the c.g.s. physical unit system, for the range of temperature between 50 deg. C. and 200 deg. C., the average thermal conductivity is 0.00366, and the average thermal diffusivity, 0.00719; for the British engineering unit system, for the range of temperatures between 120 deg. F. and 390 deg. F., the average thermal conductivity is 0.904, and the average thermal diffusivity, 0.0503. These values are for thoroughly dry concrete, of the stone-concrete mixture described.

While the values for such physical constants as thermal conductivity and thermal diffusivity, for a material like concrete, are necessarily averages, and subject to the variation of averages, yet they are probably as definite as other physical constants for structural materials, and particularly so when the average values are obtained for a considerable number of specimens, as in this investigation.

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* "A Study of the Heat Transmission of Building Materials," Univ. of Ill. Eng. Exp. Sta. Bul. No. 102, 1917.

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